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BIOPHYSICAL CHARACTERIZATION AND PREDICTED HUMAN THERMAL RESPONSES TO U.S. ARMY BODY ARMOR PROTECTION LEVELS (BAPL)

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**United States Army
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**BIOPHYSICAL CHARACTERIZATION AND PREDICTED HUMAN THERMAL
RESPONSES TO U.S. ARMY BODY ARMOR PROTECTION LEVELS (BAPL)**

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September 2013

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LIST OF SYMBOLS, ABBREVIATIONS AND ACRONYMS USED IN THIS REPORT

ACS	Army Combat
ASTM	American Society for Testing and Materials
BAPL	Body Armor Protection Level
CDD	Capabilities Development Document
CIE	Clothing and Individual Equipment
clo	thermal resistance
FRACU	Flame Resistant Army Combat Uniform
HSDA	Heat Strain Decision Aid
i_m	Vapor permeability
i_m/clo	permeability index
IOTV	Interceptor Outer Tactical Vest
m•s	meters per second
PC	Plate Carrier
RH	Relative Humidity
T_a	temperature
W	Watts
ws	wind speed

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EXECUTIVE SUMMARY

There is no debate that body armor plays an indispensable role in protecting the lives of those engaged in combat operations. However, a complex tradeoff exists between the increased survivability enabled by body armor and added weight burden that has yet to be fully understood. Soldier mobility and agility due to the added weight burden, thermal burden, and decreased agility associated with encumbering body armor. The U.S. Army has currently drafted a capabilities development document (CDD) for outlining body armor protection levels (BAPL). These BAPL configurations range from level 0 (no armor worn) to level 5+ where the full set of soft armor, front, back, and side plates are worn. The overall objective of this effort is to categorize and compare the biophysical properties of each of these configurations while wearing a standard Flame Resistant Army Combat Uniform (FRACU) with Army Combat Shirt (ACS).

This work has provided a quantified assessment of the biophysical characteristics of the currently established BAPL configurations and predictive estimates for safe maximum work intensities within three environmental conditions. These predictive modeling results show a relatively linear relationship exists between the increased protection and increased thermal burden of these various BAPL configurations. The results from this work support the recommendation to continue to seek modularization to individual protection systems to allow enable tradeoff of ballistic and thermal protection.

INTRODUCTION

Dismounted military are typically engaged in high intensity and dangerous work activities while deployed in harsh environments. In order to defend against the elements, enemy and environment, individual Soldiers in these environments are required to wear protective clothing and individual equipment (CIE). On top of a Soldier's typical clothing configurations there is a consistent demand for ballistic protection in the form of hard (e.g., ceramic plates) and soft armor materials. The ultimate goal of these protective vests is to safeguard against and mitigate injury from near-, mid-, and long-range attacks (e.g., knives, small arms fire, explosions, etc.).

There is no debate on the importance that body armor has on protecting the lives of those engaged in combat operations. There is a complex tradeoff between the increased survivability enabled by the body armor and the decreased mobility, agility, and added weight burden that has yet to be fully solved or understood. Along with this increased protection comes an associated and inherent thermal burden. That is, with increasing layers of protection it becomes increasingly difficult to dissipate excess metabolic heat to the environment.

In order to enable flexibility for varying mission demands, both the U.S. Army and U.S. Marine Corps has established the requirements for modular body armor configurations that can be readily interchanged by individual units. The U.S. Army has currently drafted a capabilities development document (CDD) outlining body armor protection levels (BAPL) (Table 1). These BAPL configurations range from level 0 (no armor worn) to level 5+ where the full set of soft armor, front, back, and side plates are worn. The overall objective of this present technical effort is to categorize and compare the biophysical properties of each of these configurations when worn with a standard Flame Resistant Army Combat Uniform (FRACU) with Army Combat Shirt (ACS).

Table 1. Description and added weights of U.S. Army Body Armor Protection Levels (BAPL) 0 to 5

Level	Configuration	Added Weight lbs/kg
BAPL 0	No body armor	0
BAPL 1	Vest or plate carrier with soft armor only	6 / 2.7 and 10.5 / 4.8
BAPL 2	Plate carrier with front and back plates	18 / 8.2
BAPL 3	Plate carrier with front, back, and side plates	23 / 10.4
BAPL 4	IOTV with front and back plates	28 / 12.7
BAPL 5	IOTV with front, back, and side plates	32 / 14.5

Note: weights based on medium sized equipment

METHODS

This work was conducted to determine the total thermal resistance (clo) and vapor permeability (i_m) and to establish a ratio of i_m/clo to establish an estimated percentage of the maximum evaporative potential of each of the five configurations and different variations of each while wearing FRACU and ACS.

Table 2. Test configurations

BAPL Ensemble Tested	Ensemble configuration
BAPL 0	Army Combat Shirt (ACS), no body armor
BAPL 1 PC	ACS, Plate Carrier Vest (PC) vest with no ballistic protective plate inserts (plates).
BAPL 1 IOTV ACS	ACS, Interceptor Outer Tactical Vest (IOTV) with no plates.
BAPL 1 IOTV FRACU	Fire Resistant Army Combat Uniform shirt (FRACU), IOTV with no plates.
BAPL 2	ACS, PC with front and back plates.
BAPL 3	ACS, PC with front, back, and side plates.
BAPL 4	ACS, IOTV with front, and back plates.
BAPL 5 ACS	ACS, IOTV with front, back, and side plates.
BAPL 5 FRACU	FRACU, IOTV with front, back, and side plates.
BAPL 5 plus	ACS, IOTV with front, back, side plates plus groin and deltoid protection.
BAPL 4 Female	ACS, Female IOTV with front and back plates.

Note: Each tested ensemble configuration included FRACU pants, brown poly boxer briefs, green cotton socks, combat helmet, Max Grip combat gloves, Oakley M frame eye protection, and desert hot weather suede combat boots. Given the variations of equipment within these BAPL a total of 11 configurations were tested (Table 2.)

Biophysical Assessments

Testing was accomplished using an articulated heated sweating manikin (Newton 20 zone, Measurement Technologies Northwest, Seattle, WA <http://www.mtnw-usa.com/> accessed 28 August 2013) located in an environmentally controlled wind tunnel. American Society for Testing and Materials (ASTM) standard F1291-10 and F2370-10 define the total thermal insulation (clo) and evaporative potential (i_m/clo) as the values measured at 0.4 m/s wind speed. For this testing, the total clo and i_m/clo were measured at three wind speeds: 0.4, 1.2, and 2.0 $m \cdot s^{-1}$ with ambient conditions of T_a 20°C and 50% RH for the clo tests and T_a 35°C and 40% RH for the i_m tests. Three replications were completed at each wind speed for each ensemble configuration. Photographs of the test set-up are shown at Appendix A, and full definitions for clo, i_m/clo are shown in Appendix B.

Predictive Modeling

Predictive modeling of human thermal responses to the various body armor configurations was conducted using the USARIEM Heat Strain Decision Aid (HSDA) (Blanchard & Santee, 2008). This modeling was conducted to simulate three environmental conditions: Desert (48.89°C; 20% RH); Jungle (35°C; 75% RH), and Temperate (35°C; 50% RH), each for conditions of full sun or no sun, and a wind speed of 1.0 $m \cdot s^{-1}$.

Simulations for the model assumed an individual male, weighing 70 kg, 172 cm tall, a surface area of 1.8 m^2 , being normally hydrated, and being heat acclimated for 12 days. During each simulation, the individual was modeled at three work intensities typical of military tasks: very light (150 W), light (250 W), and moderate (425 W) (Pandolf & Burr, 2001) (Appendix C).

RESULTS

Biophysical Results

Figure 1. Thermal resistance (clo) for the 11 ensembles configurations.

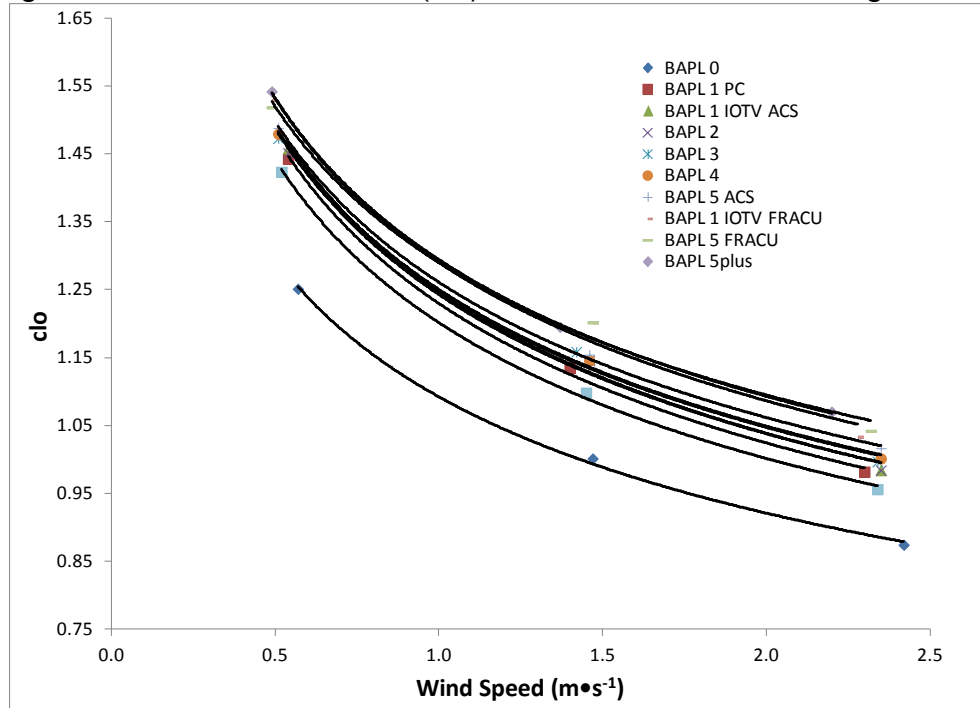


Figure 2. Evaporative potential (i_m/clo) for the 11 ensemble configurations.

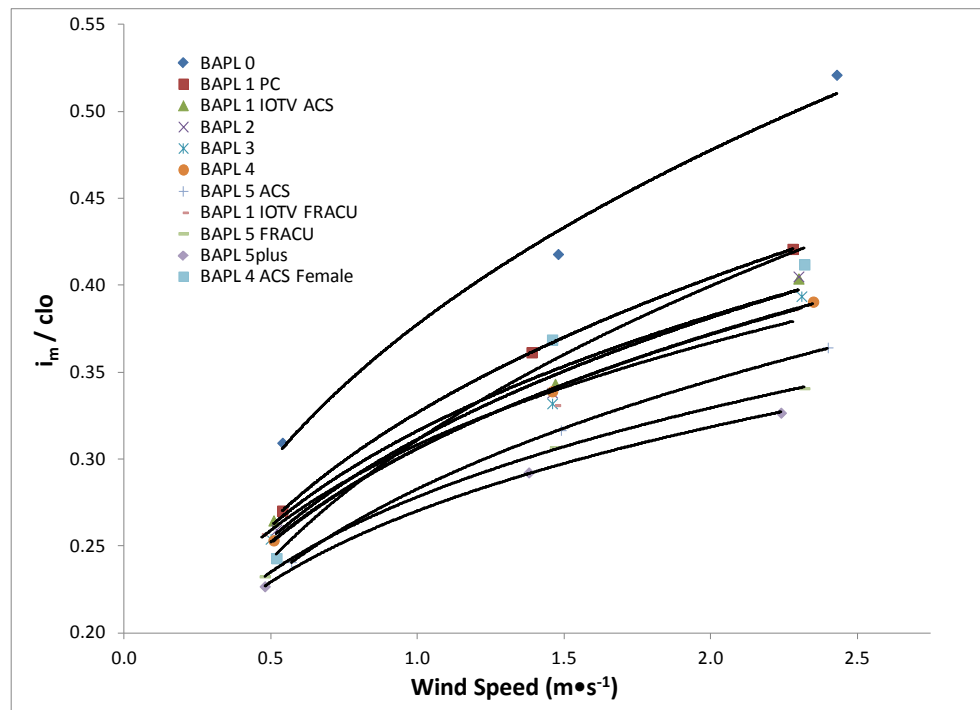


Figure 3. Evaporative potential (i_m/clo) for the 4 plate carrier ensembles.

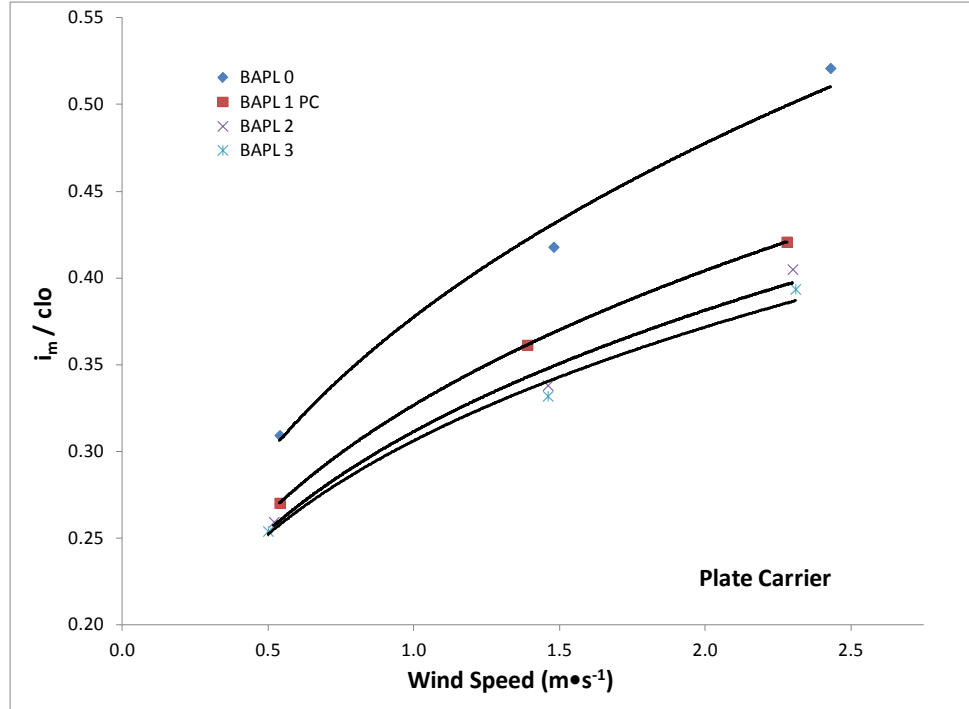


Figure 4. Evaporative potential (i_m/clo) for the five IOTV ensembles.

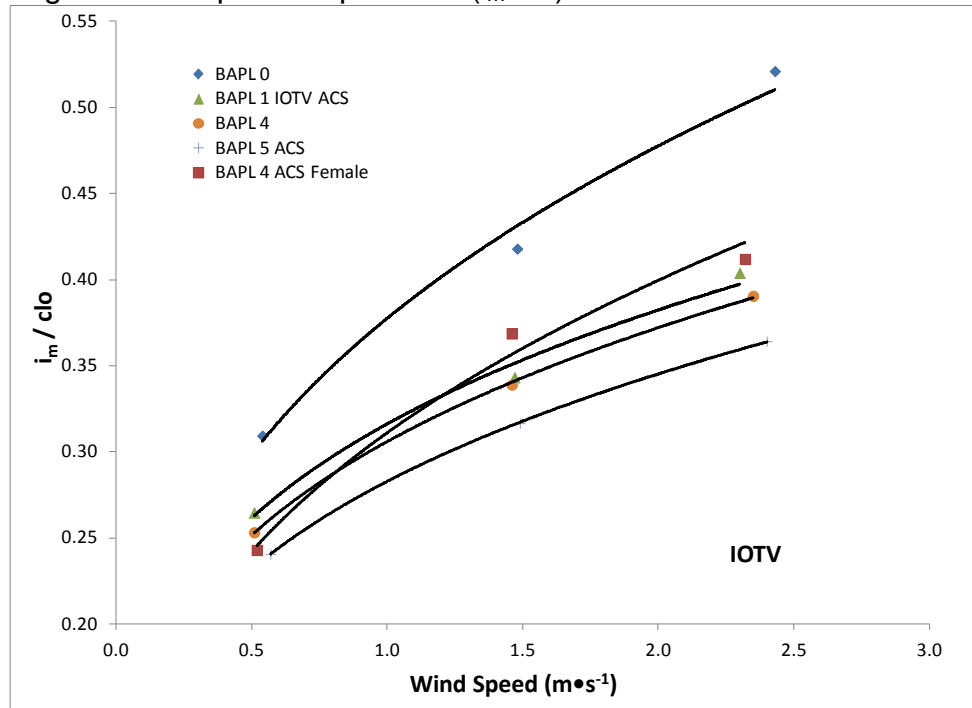


Figure 5. Evaporative potential (i_m/clo) comparison between ACS and FRACU.

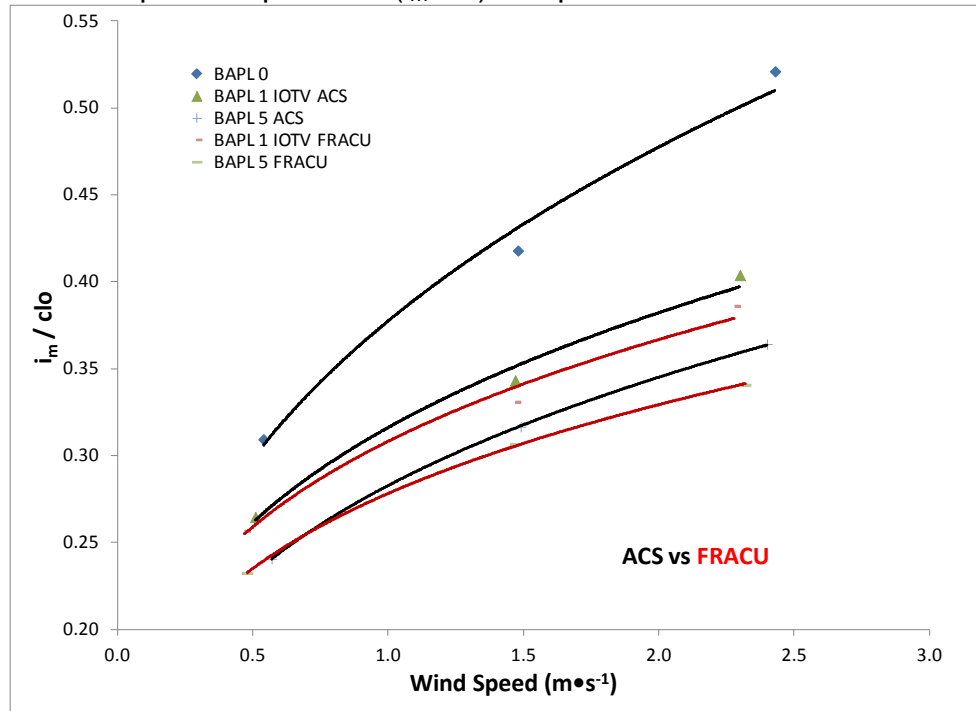


Table 3. Total thermal resistance (clo) and evaporative potential (i_m/clo) at $1.0 m \cdot s^{-1}$ wind speed for all 11 ensembles tested.

	Wind Speed			
	$0.4 m \cdot s^{-1}$ (Still air)		$1.0 m \cdot s^{-1}$	
	clo	i_m/clo	clo	i_m/clo
BAPL 0	1.37	0.28	1.09	0.38
BAPL 1	1.57	0.25	1.23	0.33
BAPL 1 IOTV ACS	1.59	0.25	1.25	0.31
BAPL 1 IOTV FRACU	1.62	0.24	1.29	0.31
BAPL 2	1.58	0.24	1.24	0.31
BAPL 3	1.57	0.24	1.25	0.31
BAPL 4	1.58	0.24	1.25	0.31
BAPL 5 ACS	1.58	0.22	1.26	0.28
BAPL 5 FRACU	1.60	0.22	1.29	0.28
BAPL 5plus	1.63	0.22	1.28	0.27
BAPL 4 ACS Female	1.53	0.22	1.20	0.31

Note: lower clo = less thermal resistance, higher i_m/clo = better evaporative potential.

Table 4 . Effect of additional layers of protection on thermal resistance (clo) and evaporative potential (i_m/clo) compared to BAPL 0.

	clo	i_m/clo
Adding BAPL 1 PC	3.0%	-3.6%
Adding BAPL 1 IOTV	3.3%	-4.4%
Adding BAPL 2	3.2%	-4.8%
Adding BAPL 3	3.3%	-5.2%
Adding BAPL 4	3.4%	-5.2%
Adding BAPL 5	3.6%	-7.2%
Adding BAPL 5plus	4.0%	-8.3%
BAPL 4 male vs. female	1.0%	-0.4%

Table 5. Effect of adding ballistic protection (plates) to the PC and IOTV on thermal resistance (clo) and evaporative potential (i_m/clo) compared to BAPL 0.

	clo	i_m/clo
Adding front and back plates to PC	0.3%	-1.2%
Adding front and back plates to IOTV	0.1%	-0.9%
Adding front, back, and side plates to PC	0.4%	-1.6%
Adding front, back, and side plates to IOTV	0.3%	-2.8%
Adding groin and deltoid protection to BAPL 5	0.4%	-1.1%

Table 6. Effect of wearing the ACS vs. FRACU under the body armor on thermal resistance (clo) and evaporative potential (i_m/clo).

	clo	i_m/clo
ACS vs. FRACU in BAPL1	0.9%	-0.6%
ACS vs. FRACU in BAPL5	0.6%	-0.4%

Predictive Modeling Results

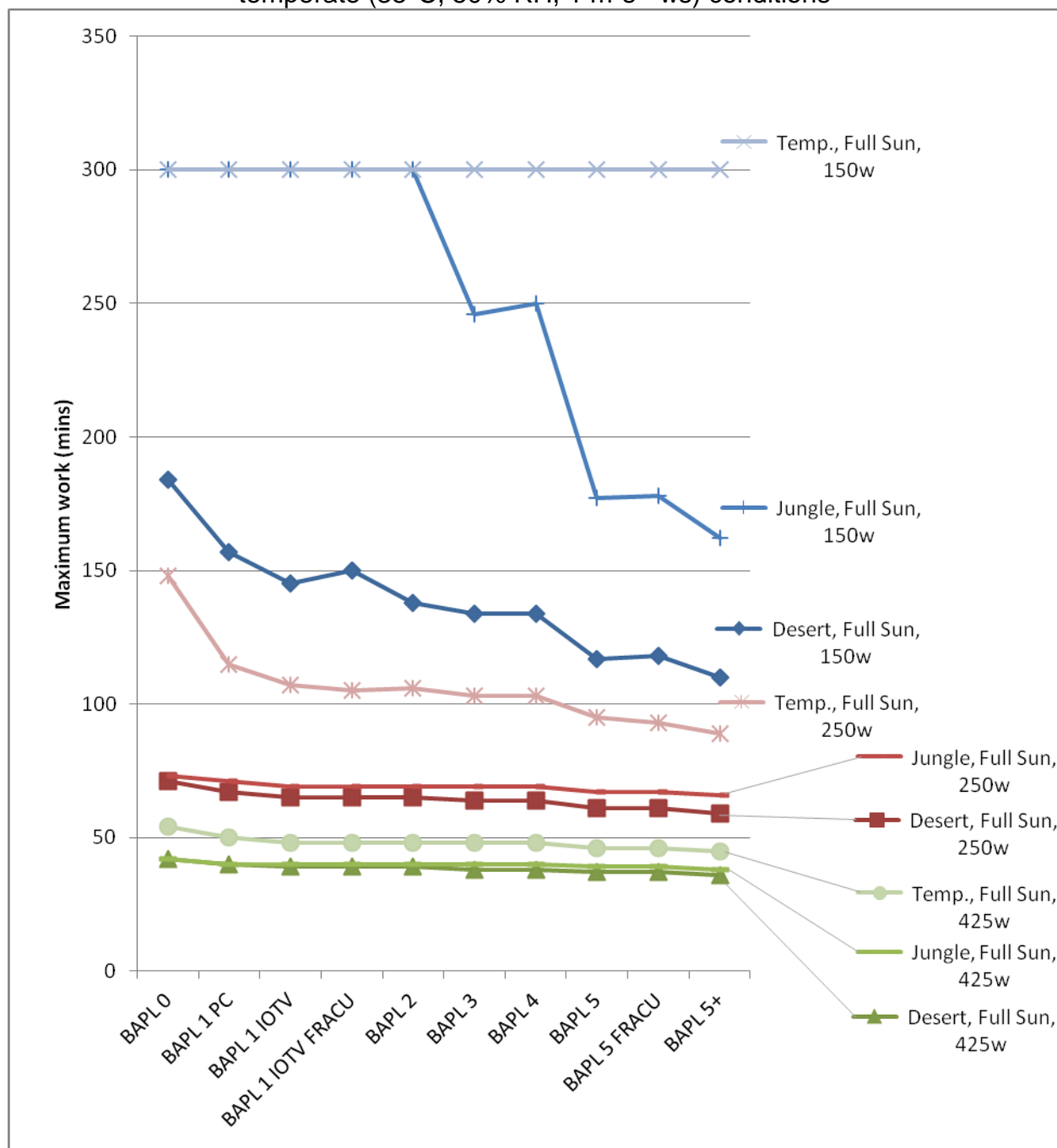
The predictive modeling of human thermal responses shows a relatively linear relationship between increased protection and decreased thermal capacity for maximal work (Table 7; Figures 6, & 7). Across each of the environmental conditions, desert, jungle, and temperate, with full sun and no sun, this relationship remained constant. While as expected the greatest impact can be observed in the hotter and more humid conditions in the sun and the least noticeable effect is seen during temperate conditions with no sun.

Table 7. Predicted maximum work times (min) for various BAPL ensembles under desert (48.89°C, 20% RH, 1 m•s⁻¹ ws), jungle (35°C, 75% RH, 1 m•s⁻¹ ws), and temperate (35°C, 50% RH, 1 m•s⁻¹ ws) conditions

		Desert		Jungle		Temperate	
		Full Sun	No Sun	Full Sun	No Sun	Full Sun	No Sun
		Max Work (min)	Max Work (min)	Max Work (min)	Max Work (min)	Max Work (min)	Max Work (min)
BAPL 0	150w	184	300	300	300	300	300
	250w	71	139	73	300	148	300
	425w	42	50	42	53	54	76
BAPL 1 PC	150w	157	300	300	300	300	300
	250w	67	108	71	185	115	300
	425w	40	47	40	50	50	65
BAPL 1 IOTV	150w	145	300	300	300	300	300
	250w	65	101	69	158	107	300
	425w	39	45	40	49	48	63
BAPL 1 IOTV FRACU	150w	150	300	300	300	300	300
	250w	65	99	69	145	105	300
	425w	39	45	40	48	48	61
BAPL 2	150w	138	300	300	300	300	300
	250w	65	100	69	156	106	300
	425w	39	45	40	49	48	63
BAPL 3	150w	134	300	246	300	300	300
	250w	64	97	69	148	103	300
	425w	38	45	40	48	48	61
BAPL 4	150w	134	300	250	300	300	300
	250w	64	97	69	148	103	300
	425w	38	45	40	48	48	61
BAPL 5	150w	117	300	177	300	300	300
	250w	61	89	67	130	95	300
	425w	37	43	39	47	46	59
BAPL 5 FRACU	150w	118	300	178	300	300	300
	250w	61	87	67	124	93	300
	425w	37	43	39	47	46	57
BAPL 5+	150w	110	300	162	300	300	300
	250w	59	83	66	120	89	300
	425w	36	42	38	46	45	56

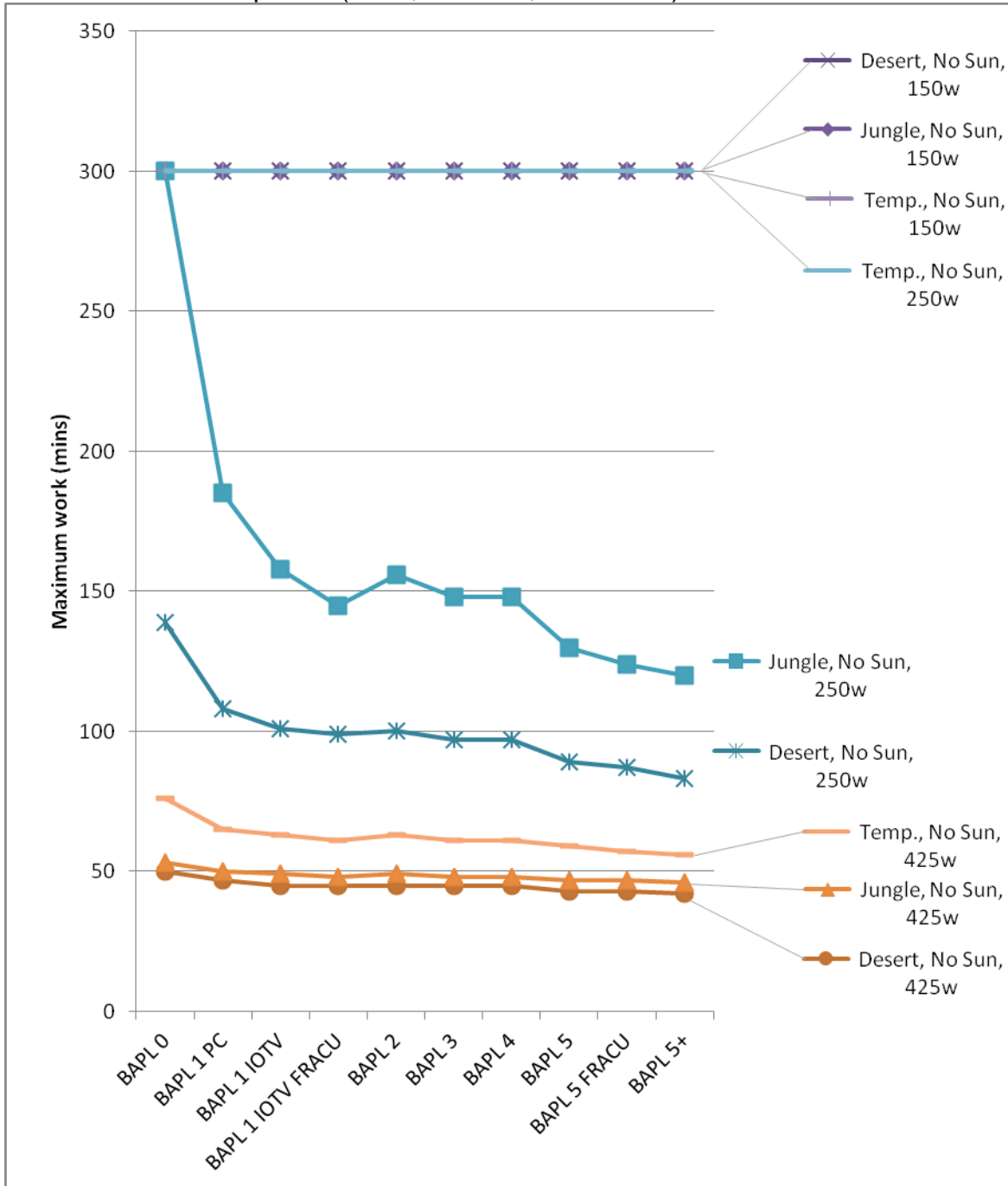
Note: the maximum predictive value for the model is set at 300 min

Figure 6. Predicted maximum work times (min) for various BAPL ensembles in full sun under desert (48.89°C, 20% RH, 1 m•s⁻¹ ws), jungle (35°C, 75% RH, 1 m•s⁻¹ ws), and temperate (35°C, 50% RH, 1 m•s⁻¹ ws) conditions



Note: the maximum predictive value for the model is set at 300 min. Desert (48.89°C, 20% RH, 1 m•s⁻¹ ws), Jungle (35°C, 75% RH, 1 m•s⁻¹ ws), and Temperate (35°C, 50% RH, 1 m•s⁻¹ ws) conditions

Figure 7. Predicted maximum work times (min) for various BAPL ensembles in no sun under desert (48.89°C, 20% RH, 1 m•s⁻¹ ws), jungle (35°C, 75% RH, 1 m•s⁻¹ ws), and temperate (35°C, 50% RH, 1 m•s⁻¹ ws) conditions



Note: the maximum predictive value for the model is set at 300 min. Desert (48.89°C, 20% RH, 1 m•s⁻¹ ws), Jungle (35°C, 75% RH, 1 m•s⁻¹ ws), and Temperate (35°C, 50% RH, 1 m•s⁻¹ ws) conditions

CONCLUSIONS

This work has provided a quantified assessment of the biophysical characteristics of the currently established BAPL configurations and predictive estimates for safe maximum work intensities within three environmental conditions.

From the biophysical assessments and predictive modeling results it can be seen that a relatively linear relationship exists between the increased protection and increased thermal burden of these various BAPL configurations. The results from this work support the recommendation to continue to seek modularization to individual protection systems to allow enable tradeoff of ballistic protection and metabolic heat dissipation.

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APPENDIX A

Figure 1. Thermal manikin wearing BAPL 0.



Figure 2. Thermal manikin wearing the Plate Carrier.



Figure 3. Thermal manikin wearing the IOTV.



Figure 3. Thermal manikin wearing the IOTV with groin and dorsal protection.



Figure 4. Thermal manikin wearing the female IOTV.



APPENDIX B

1. Definitions for clo and i_m/clo .

Resistance to heat transfer by convection and radiation is combined into one general clothing property, insulation. Insulation is expressed in an arbitrary unit, the clo. Clo is a unit of thermal insulation of clothing; standard clothes have insulation of about 1 clo, the warmest have about 4 clo.

“A clo is a unit of thermal resistance defined as the insulation required to keep a resting man (producing heat at the rate of 58 W/m^2) comfortable in an environment at 21°C , air movement 0.1m/s , or roughly the insulation of a heavy business suit. Numerically one clo is equal to $0.155 \text{ Km}^2/\text{W}$ ” (ASTM F1291-99, Rev. March 2004).

“Resistance of clothing to evaporation is expressed by the water vapor permeability index (i_m), a dimensionless index. Clothing slows the rate of vapor loss from the skin to the environment. If water vapor passes completely from the body to the environment, heat is transferred from the body to the environment. If water vapor recondenses on the skin or within the clothing, heat is not lost to the environment” (Woodcock, 1962).

The theoretical value of i_m can range from 0 for completely moisture impermeable clothing to a maximum of 1 for completely permeable clothing.

The maximum potential for evaporative heat transfer through the clothing to the environment is a function of the ratio of the permeability index (i_m) to the total insulation (clo). This ratio (i_m/clo) approximates the percentage of the maximum evaporative potential for a given environment that may be realized when wearing specified clothing.

APPENDIX C

Work Intensities of Military Tasks*

PHYSICAL WORK INTENSITY	ACTIVITY
VERY LIGHT (150 Watts)	Lying On Ground Standing in Foxhole Sitting in Truck Guard Duty Driving Truck
LIGHT (250 Watts)	Cleaning Rifle Walking Hard Surface, 1 m•s ⁻¹ , No load Walking Hard Surface 1 m•s ⁻¹ , 20 kg load Manual of Arms Walking Hard Surface 1 m•s ⁻¹ , 30 kg load
MODERATE (425 Watts)	Walking Loose Sand 1 m•s ⁻¹ , No load Walking Hard Surface 1.56 m•s ⁻¹ , No load Calisthenics Walking Hard Surface 1 m•s ⁻¹ , 20 kg load Scouting Patrol Pick and Shovel Crawling Full Pack Foxhole Digging Field Assaults
HEAVY (600 Watts)	Walking Hard Surface, 1.56 m•s ⁻¹ , 30 kg load Walking Hard Surface, 2.0 m•s ⁻¹ , No load Emplacement Digging Walking on Loose Sand, 1.56 m•s ⁻¹ , No load

Work intensities are based on metabolic expenditures:

very light = 105 to 175 watts
light = 172 to 325 watts
moderate = 325 to 500 watts
heavy = 500+ watts

*from: Medical Aspects for Harsh Environments, Vol. 1. Editors Pandolf and Burr.
"Introduction to Heat-Related Problems in Military Operations", pp 3-49. Textbooks of
Military Medicine, Office of the Surgeon General, Washington, DC 2001..